is far more expensive than laboratory testing, and laboratory testing to reduce the amount of site testing necessary is commercially sound.

(8.8) Switch Speeds

The speed of operation of non-manually operated switches is tested as a matter of routine. The speed of opening and the time taken to close and open are tested. This is necessary in order to detect any sluggish switch which, if put into service, might allow faults to remain on the system long enough to cause operation of back-up protection, resulting in unnecessary interruptions of supply.

(9) CONCLUSION

The experience of the Lancashire Electric Power Co. indicates that with a duplicate tail-end feeder system simple overload and earth-leakage protection will ensure the minimum of interruption of consumers' supplies provided adequate tests are made to prove the reliability of the gear. Where two or more feeders operate in parallel between sending and receiving stations, and provided that the load tapped off along the route does not exceed about 50% of the normal load of the feeder, very satisfactory discrimination can be obtained with parallel-feeder protective systems.

(10) ACKNOWLEDGMENT

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III. PROTECTIVE SYSTEMS FOR RURAL DISTRIBUTION UP TO 33 kV

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SUMMARY

The importance of installing suitable and efficient protective apparatus on rural networks, at all stages of their development is emphasized.

A typical protective scheme for an 11-kV and 33-kV rural distribution system which has been put into operation in a particular area of supply is described, and the reasons leading to its adoption are given.

The practical difficulties met with in securing efficient operation and of carrying out proper maintenance are discussed. Some statistical records of fault interruptions are presented. These indicate the number and type of faults causing total or partial failures of supply and show the conditions under which the protective gear is called upon to function.

The nature of the faults which occur on rural networks is analysed and a suggested standard form of keeping fault statistics is put forward for general adoption by undertakings distributing in rural areas.

(1) INTRODUCTION

In urban areas, the occurrence of faults on distribution systems inevitably results in the disconnection of relatively large numbers of consumers, even though the interruption is confined to a single distributor in a residential area. The multiplicity of interests thus affected initiates numerous courses of action on the part of individuals wanting their supply restored as soon as possible. The consequence is that many telephone calls are received or personal visits are made to the supply undertaking's offices, for immediate action to be taken to restore supply.

The number of such calls for action has generally been taken as representing the degree of importance of the occurrence, and, as a result, interruption of supply in urban areas has been considered of greater consequence than interruptions in rural areas.

Although much larger sections of the network may be affected by an interruption of supply in a rural area, due to the sparseness of population in the area, its technical features, and fewer telephones being available, there is considerably less clamour for restoration of supply.

On some occasions the supply undertaking may only become aware of an interruption of supply to a village or a section of a village, on the receipt of a postcard asking "when the supply which has been off since yesterday will be restored." This type of reaction to interruptions has not tended to create the impression that the continuity of rural supplies is an important matter, and such reaction is, no doubt, largely the result of relatively frequent faults which the consumers have come to regard as inevitable.

This attitude of mind, born of the pioneer period in rural electrification, has been undergoing rapid change in recent years. The rural consumers are beginning to expect and demand more reliable service, and the importance of rural loads is beginning to rank equally with that of urban loads.

The type of load connected in rural areas is no longer purely agricultural lighting, heating and cooking, but includes electric clocks, wireless sets, incubators, pumping and industrial loads. The interruption of supply to any of these is important to the consumer, and requires urgent action to be taken to restore supply.

These types of load require that much greater attention than was formerly considered necessary should be paid to means of protecting the distribution system against interruptions due to faults, and the selection, installation and maintenance of protective apparatus is an important factor in reducing to a minimum the number of consumers affected by an interruption. The extent to which protection can be carried depends on the amount of money which can be spent on it, and thus must, for the time being at least, be determined by local economic conditions.

(2) FUNCTION AND PLANNING OF A PROTECTIVE SYSTEM

A protective scheme for a rural e.h.v. network must cover all the high-voltage lines and apparatus connected to the system, including the main feeders or transformer bank, the main transmission lines, the ring mains or distributors, the spur lines and the high-voltage windings of transformers and all the switchgear.

The function of the protective gear is to disconnect or render harmless any fault which develops at any part of the system, with a minimum interruption of supply to consumers and with a minimum of damage to apparatus. To achieve this in a large rural area, with an interconnected network, is not as simple as would at first appear, and in every case the particular design of the network must be taken into consideration in determining the arrangement and type of protective gear.

When an area is being developed a general idea should be formed of the load to be expected, and the network so designed that when development has reached an advanced stage the sections which were constructed in the early stages fit into their proper places in the complete scheme. It should not be very difficult to anticipate, with a reasonable degree of accuracy, how the load is likely to build up under normal circumstances during the next decade or two, and to prepare a general scheme to cater for the expected output. The making of such a survey and the preparation of a scheme to deal with its requirements should make possible the selection of protective apparatus which will serve the needs of the network without undue modification or replacement, not only in the early stages but also when the loads have grown to many times the value reached in the first few years of operation. Such considerations may fully justify the installa-

tion of protective gear which, at first sight, seems unduly elaborate and complicated, but which fits well into the scheme as it takes on a more definite shape. In this way, adequate protection can be given to a network at each phase of its development without the drastic alterations occasioned when extensions are made piecemeal without reference to a comprehensive basic plan.

(3) TYPICAL PROTECTIVE SCHEME

(3.1) Description of Network

The protective scheme to be described and discussed in this paper has been applied to a network which covers an area of approximately 700 square miles. Development of the rural area began in 1926 by extension of the 6·6-kV feeders from the central urban area, but owing to the distance involved it was decided that the e.h.v. distribution should be at 11 kV. The rate of development of the rural area is indicated in Tables 1 and 2.

The load on the system has shown a steady increase, and the figures of maximum demand, units sold and annual revenue (Table 2) show the extent of the risk for which the cost of protection may be considered as a premium.

At the stage reached at present, the network comprises a main 11-kV ring which runs approximately parallel to the boundary of the area of supply. Radial feeders from a selected station feed into the ring at a number of points. Two of these radial feeders operate at 11 kV and are supplied through a bank of 6·6/11-kV step-up transformers consisting of two 2 000-kVA units, grouped together for switching purposes, and one 5 000-kVA unit. The remaining two radial feeders are 33-kV feeders, each fed by a 6·6/33-kV 7 500-kVA transformer, being connected to the 11-kV system by a corresponding 33/11-kV transformer at the remote end.

From the main 11-kV ring, spur lines and secondary rings feed the various distribution substations.

The general arrangement of the network is shown in Fig. 1.

Table 1

Year ending 31st March	Length of 6·6-kV		Length of 11-kV		Length of 33-kV	
	O.H. line	Cable	O.H. line	Cable	O.H. line	Cable
	miles	miles	miles	miles	miles	miles
1930	3·0	4·4	80·2	38·4	—	—
1935	5·2	7·6	345·2	81·3	—	—
1940	9·2	8·7	400·5	135·6	23·9	7·5

Table 2

Year ending 31st March	Maximum demand	No. of sub-stations	kVA of distribution trans-formers	Units sold	Annual revenue
	kW				£
1930	400	22	1 320	1 200 000	12 500
1935	2 797	277	11 200	7 053 000	59 300
1940	5 740	596	23 345	14 574 000	115 500

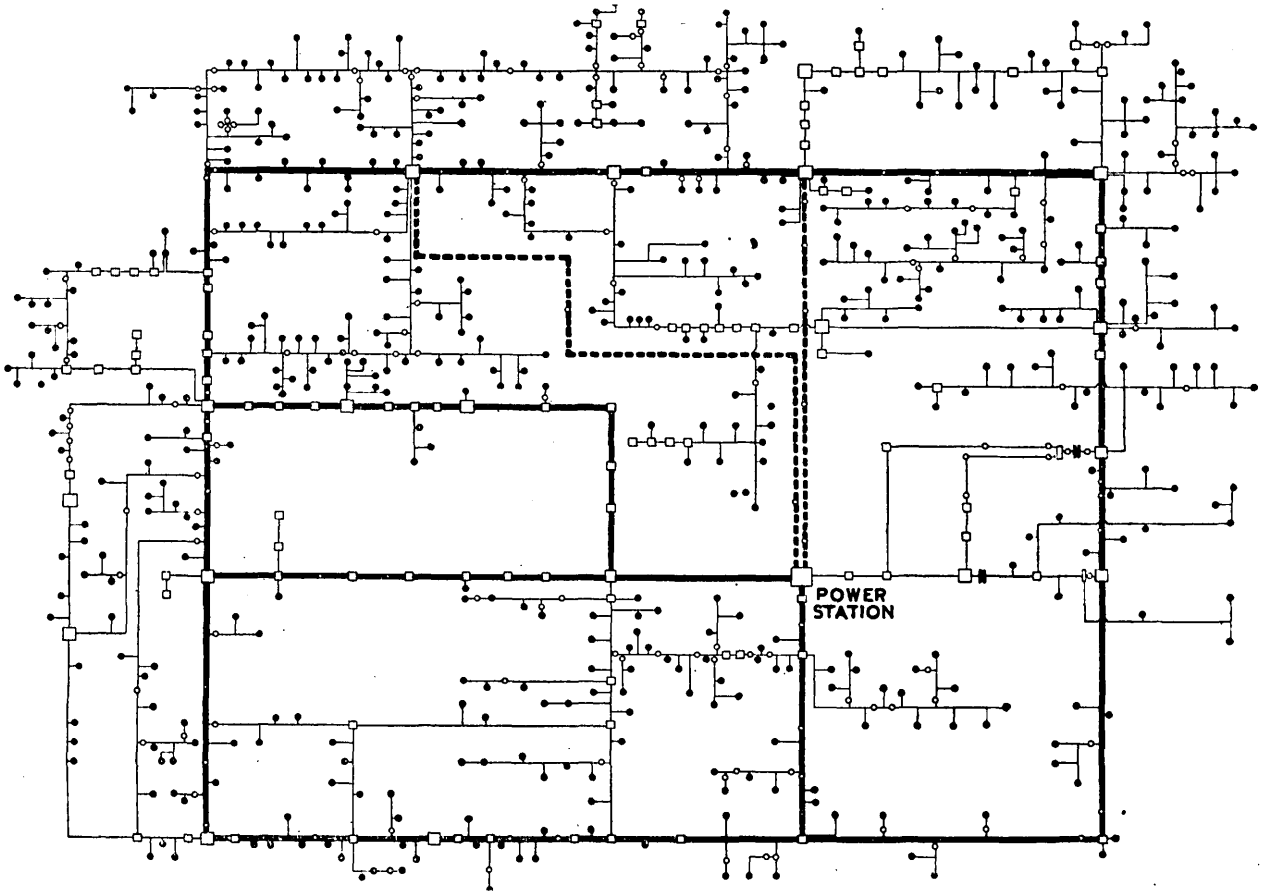


Fig. 1.—County e.h.v. network.

□ Main substations.
□ Kiosks and ring-main breakers.
● Outdoor and pole-type substations.
○ Section switches.
- - - - 33-kV feeders.
——— Main 11-kV lines.
——— Subsidiary e.h.v. lines.

(3.2) Considerations leading to the Choice of Protective Apparatus

The protection originally provided on the system consisted of over-current induction-type inverse and definite-minimum time-lag relays on the main transformers and 11-kV feeders and overload a.c. trip coils with time-lag fuses on the distributors. As was only to be expected, when a heavy fault occurred near the remote end of the network all the time-limit fuses blew together, allowing their associated switches to trip. This occasioned many delays in locating all the switches which had automatically operated, and in restoring supplies to the consumers on the healthy sections.

The problem then arose of applying a system of protection to the existing network and of selecting one which would form part of the scheme with a minimum of alteration. The network was growing at an ever-increasing rate and it was necessary that the scheme adopted should be sufficiently flexible to be adapted to the rapidly changing layout of the system. Better facilities for telephone communication between main substations was highly desirable, as existing facilities over the 24-hour period were not at all satisfactory. It was also essential, in view of the increasing short-circuit kVA available, to keep the operating time of the automatic switches to a minimum, so that the destructive effects of fault current would be minimized.

Among the limiting features was the fact that the main sections of the e.h.v. distributors to which the protection was to be applied were tapped at many places, and also the fact that the length of the sections was not sufficient to enable a time/distance system to be used with success. There were no pilot wires available for use with discriminating protective systems, and the cost of erecting separate pilot wires where the e.h.v. distributors consisted of underground cables and of modifying existing overhead lines to carry pilot wires was prohibitive.

The scheme which was finally adopted for discriminating protection on the main distributors was the "Interlock" system, and pairs of wires were hired from the Post Office, for use as pilots as well as for channels of communication. The scheme permitted each of the protected sections to be tapped with loads up to 400 kVA, and a minimum time setting sufficient to ensure discrimination between the main protection and the various types of switches controlling the spur lines. The use of the pilots as telephone lines did not interfere in any way with the functioning of the protective system, as under fault conditions the telephone instruments were immediately disconnected. The picking-up of intermittent stray currents on the pilots would not cause inadvertent tripping of the switches, and the open-circuiting of the pilots would merely tend to reproduce the old conditions under fuse protection where several switches might trip simultaneously. It was thought unlikely that the pilots would be out of commission on more than one section at once.

Subsequent to the adoption of the discriminating protection on the main distributors of the 11-kV network, the superimposing of a 33-kV transmission system became necessary, owing to the increasing load and the need for increased main step-up transformer capacity. The 33-kV transmission was initiated by the raising of the working pressure of an existing overhead line which had been designed for 33-kV operation from its temporary working pressure of 11 kV. It was not desired at that stage to incur the expense of installing 33-kV switchgear, and it was not proposed to incur the additional expense for pilot wires between the power station and a switching station which was already served with Post Office channels of communication. A scheme of protection was therefore sought which would cater for all faults on the step-up transformer, the 33-kV lines and the step-down transformer, as well as the 6·6-kV cables at the power station end, and the 11-kV cables from the transformer to the switchgear at the feeding point. The adoption of a fault-throwing scheme, together with Buchholz relays, earth-leakage relays and reverse-power relays achieved the desired result. In particular, it ensured that a fault on the 6·6-kV cables at the power station end would be entirely isolated and not be left connected to the 11-kV system through the 33-kV line and transformers, under which conditions an "arcing ground" might be set up, resulting in dangerous surges.

In view of the fact that the 11-kV network consisted largely of overhead lines, and since many of the faults occurring were of a transient nature, it was also decided to experiment with arc-suppression coils. To begin with, a small section of the network which was supplied by means of a step-up transformer from the end of the 6·6-kV network, and could, therefore, be readily isolated to form a separate system of its own, was provided with a small coil of 2·5 amp current-carrying capacity. This was later followed by the installation of a second coil on another section of the network, which was isolated by means of a 500-kVA 1/1 transformer, and a third small coil was installed experimentally on a section of the network which was isolated by means of a 300-kVA 1/1 transformer. The isolating transformers had been converted from their original function of 6·6/11-kV step-up transformers, and little expense was incurred in adapting them for their experimental purpose. The two additional coils were of 15 and 5 amp current-carrying capacity.

The statistical results of the improvement in continuity of supply were not very convincing, yet they gave a feeling of increased confidence to the engineers who were responsible for maintaining the supply. It was therefore decided to extend the protection, and a large coil which catered for the whole of the 11-kV network was installed in 1938. The small 5- and 15-amp coils were subsequently removed, and the two isolating transformers disconnected, so saving the iron and copper losses which their use entailed. The application of the arc-suppression coil to the whole 11-kV system involved, on the occurrence of a fault on one phase, the raising of the pressure of the two healthy phases to earth. In view of the extent of the network and the fact that much of the apparatus was not designed to operate under such conditions, it was decided that in the event of a persistent fault the coil should not be permitted to hold the potential of the faulty phase down to earth for any length of time until the fault was cleared by hand. Arrangements were therefore made to connect an earthing resistance across the coil by means of an automatic switch when a fault persisted for more than 5 sec., so that the faulty section would be isolated by the operation of the normal protective gear.

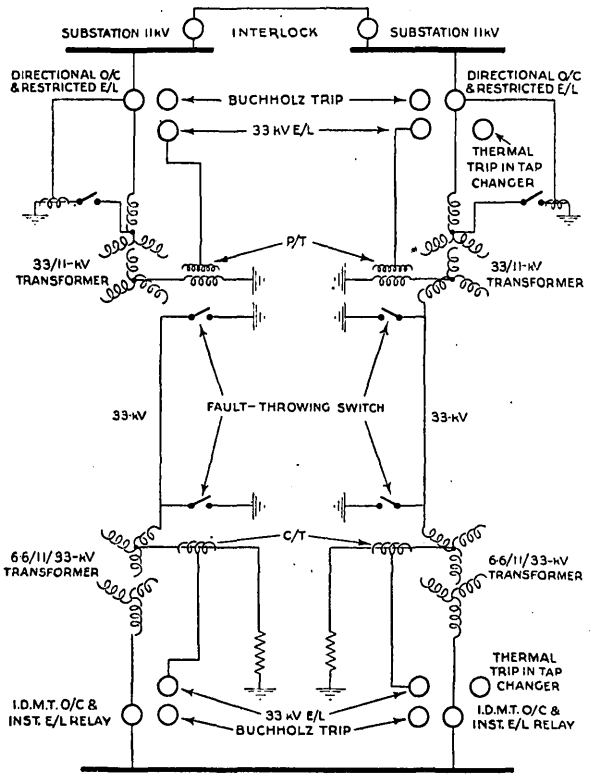
(3.3) Types of Protective Apparatus Installed

(3.3.1) Main Transmission Lines and Transformers.

The protective apparatus provided on the main 6·6/11-kV transformers consists of simple over-current and earth-leakage induction-type inverse and definite-minimum time-lag relays installed on the 6·6-kV side. Over-current protection is provided on all three phases, the earth-leakage relay being a separate unit, and intertripping connections to the 11-kV switches ensure the complete isolation of the transformers in the event of an internal fault.

The 33-kV transmission lines and their associated transformers are treated as a single unit for the purpose of protection, by adopting a fault-throwing system whereby intertripping between the 6·6-kV circuit-breaker at the generating station and the 11-kV circuit-breaker at the remote substation is effected by deliberately throwing an earth on one phase of the 33-kV system.

The arrangement is shown in Fig. 2, and it will be noted that at the generating station end of the feeder inverse time-lag over-current and instantaneous earth-leakage relays are installed on



6·6-kV, 500 000-kVA bars at power station.

Fig. 2.—Schematic diagram of 33-kV feeder and transformer protection.

the 6·6-kV side of the transformer. The operation of either of these relays, in addition to tripping the 6·6-kV circuit-breaker, also releases a spring-operated air-break switch which earths one phase of the 33-kV winding of the transformer. On the 33-kV side of the transformer a current transformer mounted on the star-point connection which is earthed through a 50-ohm liquid resistance is connected directly to an earth-leakage relay which trips the circuit-breaker but does not operate the fault-throwing switch. A short time-delay is imposed on this relay to avoid operation due to transient faults.

At the substation end, directional over-current and restricted earth-leakage relays are installed, and between the star point on the 33-kV winding of the transformer and earth a single-phase voltage transformer is connected. The secondary winding of this voltage transformer is connected to an earth-leakage relay. A fault-throwing switch similar to the one at the generating station is operated by the directional and restricted earth-leakage relays only.

Earth faults on the 33-kV line are cleared by operation of the earth-fault relays connected on the 33-kV side of the transformers, operating current being provided respectively by the neutral-current transformer and by the raising of the potential of the star point of the transformer at the substation end.

Phase faults on the 33-kV line and phase or earth faults on the 6·6-kV and 11-kV switchgear and connecting cables are dealt with by the over-current and earth-leakage relays, intertripping between the circuit-breakers being effected by the fault-throwing switches, thus ensuring the complete isolation of the fault. In addition the transformers themselves are protected by means of Buchholz relays provided with both gas and surge floats. Operation of the gas float by gradual accumulations of gas causes visual alarm to be given by an indicator at the substation in the case of the substation transformers, and audible alarm at the power station in the case of the power-station transformer. The surge float, which would be operated by the sudden giving off of gas in the case of an internal fault on the transformer, causes the adjacent 6·6-kV or 11-kV oil circuit-breaker to trip instantaneously, and at the same time operates the 33-kV fault-throwing switch, so bringing out the remote oil circuit-breaker and completely isolating the particular feeder.

This system has been found to give excellent results in practice, and burning of the fault-throwing switch contacts has been found to be very slight.

(3.3.2) **11-kV Main Distributors.**

The two 11-kV radial feeders are both tapped along their route and are, therefore, in reality 11-kV distributors. These two feeders, together with 8 sections of the main ring, are now operated as an interconnected circuit. Ten of the sections of the ring thus formed are equipped with "Interlock" protection, the remaining sections being protected with inverse-time over-current relays. Back-up protection is provided by over-current relays at a number of points on the ring. These have fairly long time-delays and serve merely to guard against failure of the interlock protection and faults outside the zone of the feeder protection.

The remaining sections of the circumferential ring are kept sectionalized and protected by inverse definite-minimum time-lag over-current relays.

The general arrangement of the protection on the 11-kV system is shown in Fig. 3.

The principle of the interlock feeder protective system is based on a comparison of the direction of a fault current at either end of a feeder. If a fault current flows into one end of a protected section of a ring main and at the same time flows out of the section at the other end, then that section must be healthy and the protective relays must be prevented from operating and isolating the circuit by means of a stabilizing impulse or signal transmitted along pilot lines to the opposite end. If, however, fault current flows in opposite directions at the two ends, the feeder is faulty, and as no stabilizing signal is transmitted under

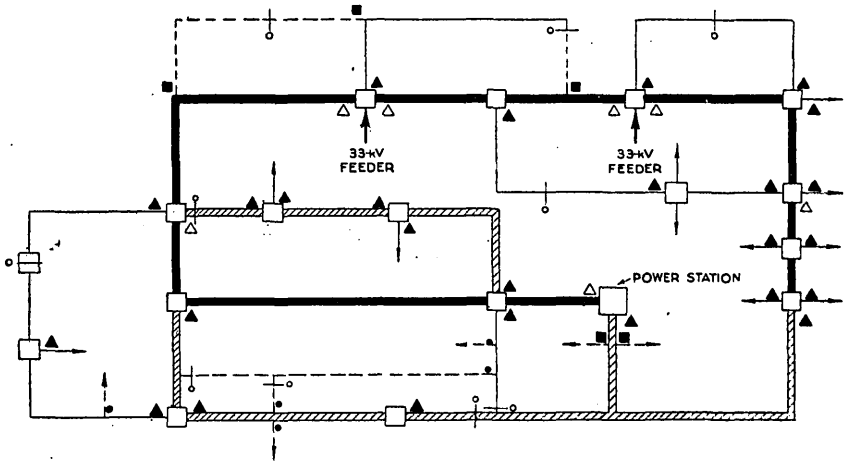


Fig. 3.—Schematic diagram of 11-kV system protection.

Interlock sections.
Main lines protected by I.D.M.T. relays.
Secondary lines protected by I.D.M.T. relays.
Secondary lines protected by a.c. trip coils.
I.D.M.T. relays.
Back-up relays.
A.C. series trip coils.
A.C. shunt trip coils.
Section switches (normally kept open).

these conditions the protective gear trips the oil circuit-breaker. The relays, comprising the equipment at each end of the protected section, include:—

(*a*) A two-stage non-directional phase-fault relay.
(*b*) A directional relay.
(*c*) An earth-leakage relay.
(*d*) An auxiliary operating relay.
(*e*) An auxiliary stabilizing relay.
(*f*) A lock-out relay.
(*g*) A definite time-lag or hesitation relay.

The occurrence of a fault operates the first stage of the 2-stage over-current or earth-leakage relay. This operation applies potential to the directional relays, the contacts of which open when current flows into the feeder and close when it flows out. If the contact remains closed the stabilizing relay operates, the telephone is disconnected and the 30-volt insulated battery is connected across the pilots to send a stabilizing signal. If the contact of the directional relay opens, the operation of the second stage energizes the operating relay which, in turn, starts the time-hesitation relay, but in addition it connects the lock-out relay across the pilots. If a stabilizing signal has been transmitted from the remote end, operation of the lock-out relay takes place, the time-hesitation relay circuit is de-energized, and the circuit-breaker remains closed.

In the case of a fault on the protected feeder, current flows into the feeder from each end; this opens both of the directional relay contacts and allows complete operation of the over-current or earth-leakage relays. No stabilizing signal is transmitted as neither stabilizing relay is energized, and after the interval provided by the time-hesitation relay both circuit-breakers are tripped.

When the fault is in a section other than the protected section, the directional relay contacts will open at the end of the feeder at which current flows into the feeder, and close at the opposite end. These operations result in the operating relay being energized at one end and the stabilizing relay being energized at the other. A stabilizing signal is thus transmitted from the far end of the feeder where the circuit-breakers will not trip because the operating relay has not been energized, is received by the lock-out relay at the near end, de-energizes the time-hesitation relay, and prevents the tripping of the circuit-breaker.

In the equipment first installed, the time-hesitation relay was of the definite-time type, but in later installations this is omitted and the second-stage over-current or earth-leakage relay is of the induction-disc pattern, giving a delay having an inverse time characteristic with a definite minimum time-lag.

Post Office pilot wires are used for conveying the stabilizing impulses from one end of a section to the other in the majority of sections, but in two sections, where the main line consists of underground cable, pilot cables have been laid by the Corporation.

The use of Post Office pilots necessitates special precautions to prevent dangerous or harmful potentials getting back to the Post Office system under fault conditions. This is accomplished by separating the operating coils of the relay from the contacts with insulating barriers which must be capable of withstanding 15 kV momentarily and 5 kV for 2 minutes.

Where the pilots are owned by the Corporation the high degree of insulation is unnecessary, and the whole of the equipment is considerably simplified in consequence.

The equipment also includes fault indicators and a lock-out relay-operation counter, indicating the number of straight-through faults dealt with by the equipment. Fig. 4 shows the connections for the "Interlock" system of protection.

(3.3.3) **11-kV Subsidiary Distributors and Spur Lines.**

Subsidiary distributors radiating from the section points on the ring main or from the terminal points of the 33-kV main transmission lines or e.h.v. feeders are protected by induction-type inverse definite-minimum time-lag relays.

Spur lines are protected by oil circuit-breakers fitted with series coils or fuses of the carbon-tetrachloride type and sometimes are even connected direct to the e.h.v. distributor, depending on the location, length and importance of the particular line. Some of the oil circuit-breakers are of the automatic-reclose type, but the installation of this class of switch has been generally retarded by war-time economic considerations.

On certain spur lines considerable lengths of overhead construction have been replaced by underground cable. These spur lines usually have small transformers varying from 10 kVA to 50 kVA connected to them, and it has been found that where such lines are protected by tetrachloride-type fuses the blowing of one fuse due to a single-phase fault results in an abnormally high voltage appearing across the secondary of the transformers, particularly when they are lightly loaded. This abnormal voltage may be as much as 50% in excess of normal, and is due to voltage resonance between the cable capacitance and the transformer inductance. This may be explained by considering the circuit to be reduced to an inductance and capacitance in series. If an alternating voltage is applied across this circuit and gradually raised in value, at a certain critical voltage dependent on the inductance and capacitance values of the circuit, resonance will suddenly take place, resulting in an abnormal increase in current and a corresponding abnormal increase in voltage across the inductance. It so happens that in certain of the spur lines mentioned, the values of the cable capacitance and transformer inductance are suitable for resonance at about the phase-to-neutral voltage of the system. It has therefore been necessary to adopt a means of protecting these lines which will ensure that on the occurrence of a fault all three phases are interrupted simultaneously. This protection usually takes the form of a pole-mounted oil switch.

(3.3.4) **Distribution Transformers.**

The individual substations, mainly consisting of pole-mounted equipment, are protected by fuses, with a few exceptions where the transformer is connected direct to the line. This practice has only been adopted on short spur lines where a number of substations are relatively closely grouped, the group being treated as a whole for the purpose of protection. On many of the older substations the fuses are of the rewireable type, but all those erected during the last few years are of the tetrachloride type. It has been found necessary to pay special attention to the type of fuse-holder employed, as experience has shown that with the superimposing of the 33-kV transmission system on the network, and the consequent increase in available short-circuit kVA, certain types of spring-clip holders, even if provided with safety catches, are not strong enough to retain the fuses against the mechanical forces set up by the short-circuit currents. In positions near to the 33-kV feeding points a type of holder employing roller contacts which firmly grip the ends of the fuses has been found more satisfactory than the spring-clip type.

(3.3.5) **Arc-Suppression Coils.**

An arc-suppression coil is designed to prevent a power arc following a transient fault by neutralizing the capacitance of the network. The coil, which is connected between the neutral point of the system and earth, has an inductance such that on the occurrence of an earth fault the reactive current caused to flow through it by the potential of the neutral point which is raised to phase voltage is equal and opposite to the sum of the capacitance currents of the two sound phases. Theoretically, therefore, the current in the fault and the voltage difference between the fault and

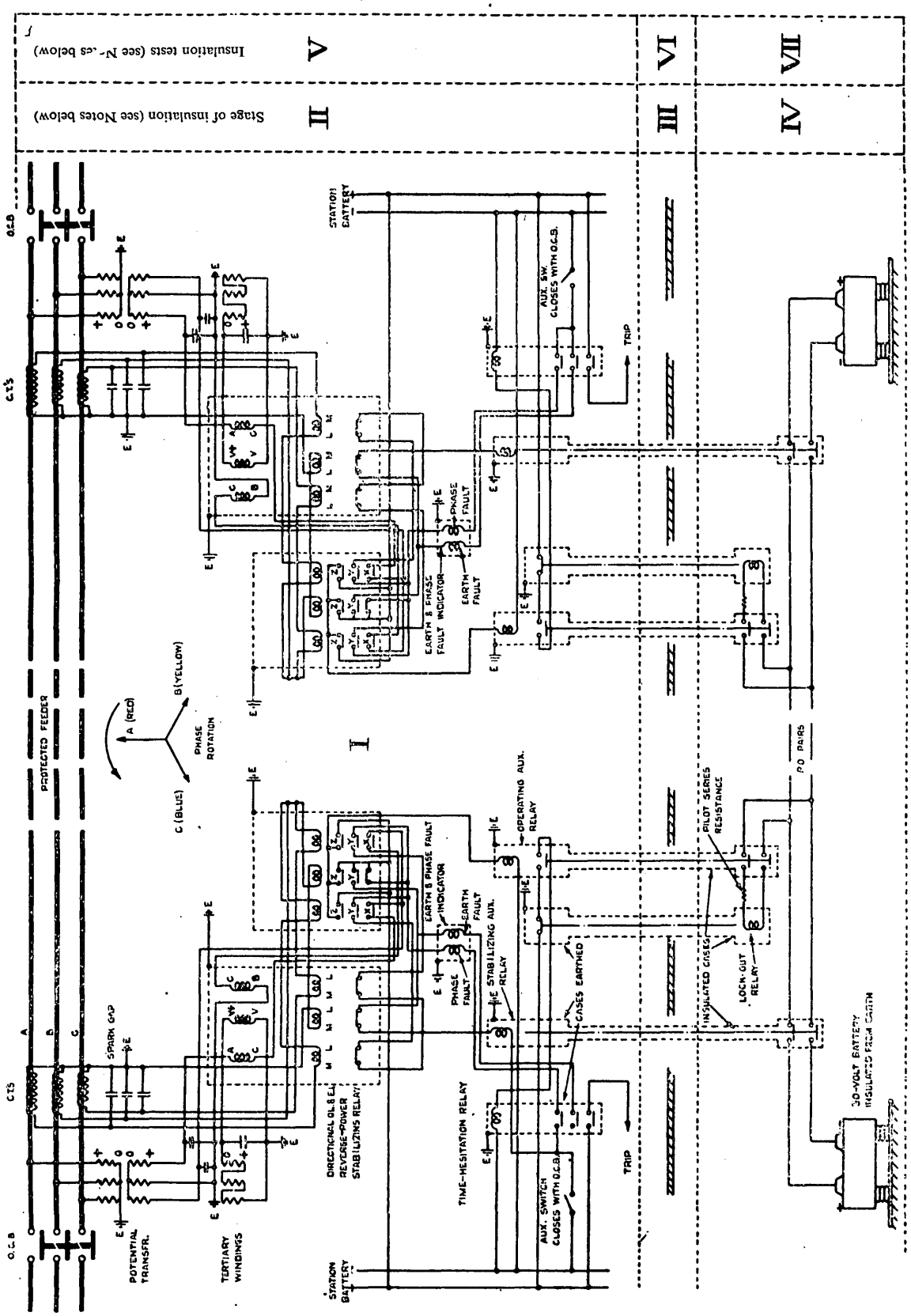


Fig. 4.—Diagram of connections of interlock protection using P.O. pairs and physically separated relays.

NOTES:—I. Two-stage O.L. and E.L. relay. Contacts X and Y bridged at a low fault-current setting. Contacts X, Y and Z bridged at a higher fault-current setting. II. Earthed enclosure. III. Physical separation of relay parts with insulating barrier between coils and contacts. IV. Physically separated stage. Insulated enclosure. V. The following parts to withstand the appropriate B.S. test pressure to earth, namely 2 000 V for 1 min, transformer l.v. windings, relay coils and contacts, circuit-breaker auxiliary switches, wiring. Cases and metal parts to be earthed. Protected spark gaps to break down at 400/750 V. Wiring run as in standard practice. VI. Between coils and contacts 15 kV momentarily; 5 kV for 2 min. VII. Wiring to be of 2 200-V grade cable run on insulated cleats. All parts, including wiring, to withstand P.O. test pressure to earth of 15 kV momentarily and 5 kV for 2 min.

earth will be reduced to zero, but in practice there will remain a small residual current in the arc, due to losses and leakages in the reactor and lines. If the fault is of a transient nature this will not be sufficient to maintain the arc. To clear a persistent fault, a normal earthing resistance may be switched in after a short time-delay.

The coil is provided with tappings for tuning purposes, and the selection of the best tapping is carried out by measuring the current in the neutral under normal conditions. When the coil is most nearly in tune, i.e. nearest to a resonant state, out-of-balance on the network will appear to reach a maximum value. Thus the highest value of neutral current recorded indicates the best tapping to use. Once the coil has been initially tuned, it is only necessary to make an occasional test to ensure that a reasonable degree of tuning has been maintained, and unless the characteristics of the network have altered little further attention should be necessary.

The occurrence of a fault is indicated on a recording instrument connected across a secondary winding on the arc-suppression coil; and, if another recorder is connected across a current transformer slipped over the earth-resistance connection, a comparison of the charts will indicate transient faults cleared by the coil and those permanent faults which have to be cleared by the operation of the normal protective gear.

Table 3

TESTS ON ARC-SUPPRESSION COIL

Test number	11	15	17	35	36
Type of fault ..	2-in gap over insulator bridged by 10-amp fuse wire. Red phase	1½-in gap over insulator bridged by 10-amp fuse wire. Red phase	1½-in gap over insulator bridged by 10-amp fuse wire. Red phase	Solid. Red phase	Solid. Red phase
Suppression coil tapping number	5 Optimum value (162 amp)	7 + 29·6% optimum value	1 − 35·2% optimum value	5 Optimum value	7 + 29·6% optimum value
Fault current ..	190 amp (max. inst. value)	Variable	250 amp (max. inst. value)	30 amp (steady value)	50 amp (steady value)
11-kV neutral voltage	6·0 kV	4·5 kV	6·35 kV	6·35 kV	6·35 kV
Clearing of faults ..	Slight arc cleared quickly after 4 cycles	Small arc clearing after 1 cycle	Small flash arc cleared after ½ cycle	Fault cleared by hand after 57 cycles	Fault cleared by hand after 88 cycles
Effect on network ..	Network oscillates considerably before settling to normal	Slight oscillations on network. Normal after 7 cycles	Pronounced oscillations on network, lasting about ½ sec	Fault kept suppressed	Fault kept suppressed
Oscillogram Nos. (see Fig. 5)	—	15c and 15t	17c and 17t	—	36c and 36t
Operation	Correct	Correct	Correct	Normal	Normal

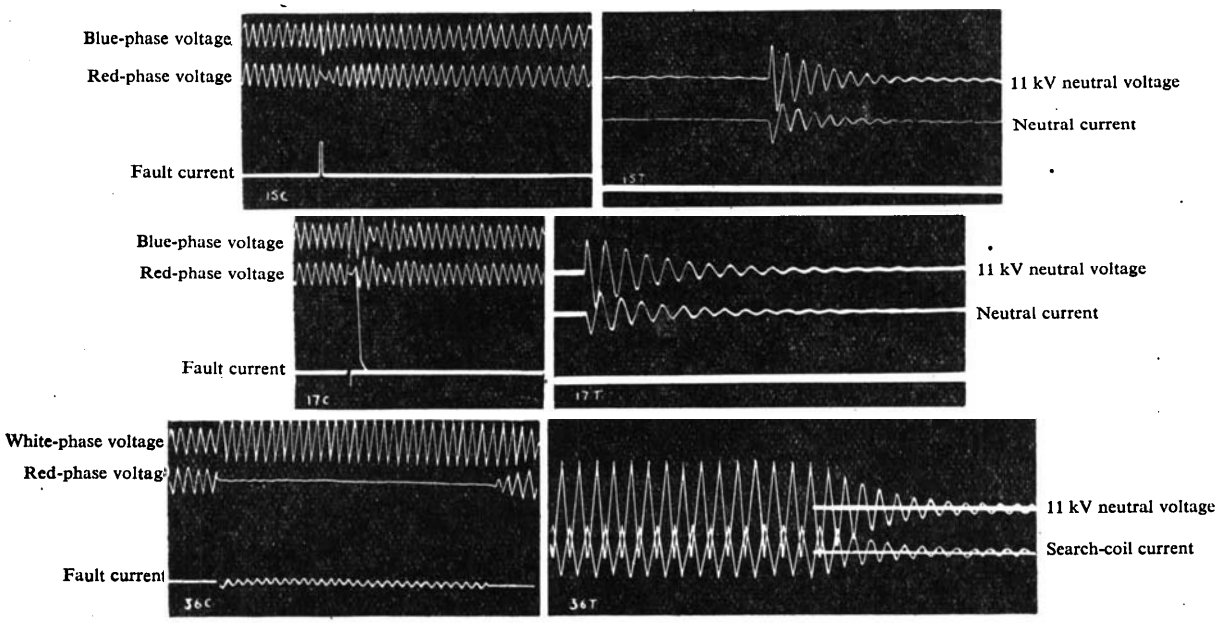


Fig. 5

A series of tests was carried out on the coil installed to protect the whole of the 11-kV network under review. These tests included observations of the operation of the coil in clearing arcs struck across insulators, and measurements of the residual current in permanent faults. Samples of results are given in Table 3 and reproductions of oscillograms in Fig. 5. These tests show that satisfactory operation is obtained over a wide range of adjustment.

(3.4) Operation and Maintenance Difficulties

Protective gear, unlike most electrical gear, is inactive for the major portion of its life, but it must be in a condition to come into operation at the very instant required. It is therefore of the utmost importance that efficient maintenance be carried out to ensure that relays and operating coils are kept free from dust, rust or other corrosion which would result in moving parts becoming sticky or sluggish in action. Contacts must be kept clean, and steps must be taken to see that tripping batteries are always fully charged. In addition to frequent cleaning on site, it is desirable to change the relays at intervals of about three years so that they may have a complete overhaul and inspection in the test room.

Routine tests may be carried out by secondary injection, but, wherever possible, primary injection, which brings the current transformers within the range of the test, should be carried out at intervals.

This testing of protective gear should occupy the whole time of a competent engineer on supply networks of any size, but very often the work has to be undertaken as a side-line by an engineer engaged on other duties, with the result that it is often neglected.

Maintenance of protective gear is even more difficult in rural areas than in urban areas, chiefly owing to the distances between substations and the time taken in travelling between them. It is therefore necessary to take exceptional precautions to see that protective apparatus is not affected by dampness, and it has been found helpful to provide slight local heat in the neighbourhood of relays and trip coils in substations and kiosks. This is usually done by short lengths of tubular heater installed in a convenient position below the apparatus.

Time-lag fuses have been a source of trouble, owing to the deterioration of the fuse wire or corrosion of contacts. No attempt is made to secure discrimination by time-lag fuses as this has been found unreliable. This time-lag fuse is only used to prevent operation due to momentary disturbance on the system.

The changing of trip batteries for recharging has been made unnecessary by the installation in all rural substations of trickle chargers with metal rectifiers. This has eliminated a considerable amount of labour and ensures that the batteries are always in a fully-charged condition. Topping-up and general inspection is carried out when the protective gear is inspected.

A difficulty in operation which has caused considerable trouble on the system described is the failure of pilots which are rented from the Post Office. This results in a failure of the protective gear to stabilize on through-fault currents, and causes healthy sections of the network to be tripped out unnecessarily. A system of automatically testing the pilots every half-hour has been used, and in the event of the alarm sounding it is necessary to travel round the main ring to determine which section is faulty. In spite of the excellent service normally given by the Post Office maintenance staffs, there have been periods when the pilots were out of commission for some time. Another factor is that very often the cause of a fault on the power system also puts the pilot circuits out of use, particularly on overhead circuits; underground circuits have been found exceedingly reliable.

Observation of the operation of protective gear is most important so that records can be kept and inadvertent operation investigated. The latter can only be carried out if the mains engineers take careful note of the indicators on the relays before resetting when they are actually dealing with a fault The general tendency seems to be that they are so anxious to get the supply restored that observations have frequently been neglected, and it has been necessary to insist that attention be paid to this matter even though it results in a small extension of the time of interruption of supply.

(3.5) Records of Faults

Checking the operation of a protective system is closely connected with the recording of the actual faults which have occurred, and, in addition, remedial measures which experience dictates need to be applied to the system come under the general heading of protection.

It is therefore proposed to describe the system which has been evolved to classify and obtain statistics relating to faults of different types. Faults are classified and numbered under the following headings:—

A. *Overhead line faults.*
   (1) Special causes due to abnormal conditions.
   (2) Birds.
   (3) Trees.
   (4) Insulation failure.
   (5) Lightning.
   (6) Mechanical failure.
   (7) Unclassified.

B. *Cable faults.*
   (1) Joints.
   (2) Pole boxes.
   (3) Mechanical damage.
   (4) Unclassified.

C. *Switchgear faults.*
   (1) Electrical.
   (2) Mechanical.

D. *Transformer failures.*

E. *Faults due to unknown causes.*

F. *Faults due to enemy action.*

G. *Faults which do not come under any of the above headings.*

Many of the above classes can occur on either the e.h.v. or l.v. systems and indication is given, e.g. a fault caused by a bird on the e.h.v. system would be classified as E.H.V./A(2).

The best indication of the extent of an interruption due to a fault is given by the number of consumer-hours lost, but to obtain this information a great deal of computation is involved, and it is found simpler to use the number of substation hours interruption as a guide. This figure is, in general, easily obtained from the records of switching times and forms a useful comparative basis.

Table 4 gives for the past three years the figures for faults on the e.h.v. network described above.

The analysis is extended in a similar manner to cover the central urban areas and also faults on the l.v. system. A further comparison on a district basis is prepared each year on the lines shown in Table 5. This Table, which is used to assess the percentage of continuity of supply, includes l.v. faults as well as e.h.v. faults.

Table 6 gives the total summary of rural-area faults on the e.h.v. and l.v. systems, extending over a number of years.

Examination of a fault analysis set out on the lines suggested immediately reveals the types of fault which are causing the

Table 4

ANNUAL FAULT ANALYSIS

Classification (see page 17)	1939			1940			1941		
	No. of faults	Substation-hour interruptions	Substation-hours per fault	No. of faults	Substation-hour interruptions	Substation-hours per fault	No. of faults	Substation-hour interruptions	Substation-hours per fault
A(1)	13	1 128·16	86·8	46	3 341·5	72·7	6	425·87	70·84
A(2)	10	97·1	9·7	9	129·0	14·3	10	123·02	12·3
A(3)	6	118·18	19·7	12	515·7	42·9	4	36·72	9·18
A(4)	10	468·87	46·9	17	353·5	20·8	9	284·82	31·65
A(5)	122	1 975·08	16·2	36	844·8	22·5	19	215·71	11·32
A(6)	—	—	—	8	70·6	8·8	5	200·0	40·0
A(7)	1	32·8	32·8	3	100·3	33·4	14	500·86	35·7
B(1)	—	—	—	9	262·5	29·5	3	42·4	14·13
B(2)	3	106·5	35·5	7	289·0	41·3	11	1 189·39	108·13
B(3)	—	—	—	—	—	—	2	32·5	16·25
B(4)	2	43·3	21·7	—	—	—	—	—	—
C(1)	4	59·11	14·8	10	711·2	71·1	14	598·0	42·7
C(2)	—	—	—	2	77·7	38·9	—	—	—
D	2	14·66	7·3	1	16·1	16·1	3	12·23	4·06
E	31	265·98	8·6	45	1 416·0	31·5	25	719·29	28·8
F	—	—	—	1	113·6	113·6	7	490·47	70·07
G	1	12·5	12·5	5	203·7	40·7	9	92·18	10·24
Totals	205	4 322·24	21·1	211	8 445·2	40	141	4 963·46	35·2

Table 5

DISTRICT FAULTS SUMMARY—1941

District	No. of faults	No. of substations in district	Substation interruptions	Average substation interruptions per fault	Substation-hour interruptions	Average substation-hour interruptions per fault	Average duration of fault, hours	Per cent continuity of supply
Eastern ..	113	328	1 423	12·60	2 705·96	24·22	1·92	99·90
Western ..	55	326	1 167	21·20	2 268·31	41·2	1·94	99·92
Central ..	15	96	42	2·80	101·48	6·76	2·41	99·98
Totals ..	183	750	2 632	13·8	5 075·75	27·70	2·0	99·92

Table 6

ANNUAL FAULTS SUMMARY

Year	1936	1937	1938	1939	1940	1941
No. of faults	136	115	180	214	242	183
Substation interruptions ..	3 146	1 558	2 909·4	3 458·5	4 735·9	2 632
Substation-hour interruptions	2 037	2 661	2 310·5	6 153·7	8 542·2	5 075·75
Per cent continuity of supply	99·96	99·95	99·96	98·89	99·85	99·92

greatest interruption of supply. This may not always be the one that shows the greatest number of actual faults, but it takes into account also the time required for repair and complete restoration of supply. The preventive action to be taken may be considered as a part of the protection of the system, and matters that have and are receiving attention are indicated.

(3.6) Preventive Measures—Applied and under Consideration—for Reducing the Number of Faults

(3.6.1) Arc-Suppression Coils.

In the early years of rural supply it was found from the fault analysis that the greatest outage due to any one cause was that occasioned by lightning, and as a consequence the arc-suppression coil, previously described, was introduced to protect the whole 11-kV system.

Table 7 shows the effect of the coil which was connected in 1938.

From the statistics for the past three years it will be noted that, apart from the large increase in the first year of working, probably due to weak spots being overstressed, faults due to lightning have been considerably reduced, but these still remain one of the greatest single sources of trouble. The installation of the coil has, however, greatly reduced the amount of damage to apparatus following flashovers due to lightning. Examination of the

INTERRUPTION OF SUPPLY.

Report No.....
Part A.
To be sent to Head Office within 24 hours of occurrence.

The supply to.....

.....

was interrupted from.....on.....194 , to.....on.....194 .

Substation interruptions ..... Duration.....

Notice sent to Electricity Commissioners (if necessary) Date .....

General description of interruption.....

.....

.....

.....

.....

.....

.....

.....

Date..... Signed.....
District Engineer

FOR HEAD OFFICE USE Date received.....

Report examined by	Initialled	Date
Mains Superintendent		
Technical Assistant		
Deputy City Electrical Engineer		
City Electrical Engineer ..		

Reported to..... Date.....
(Factory Inspector or other Govt. Dept. when necessary)

Filed..... Initial.....

INTERRUPTION OF SUPPLY.

Report No.....
Part B.
To be sent to Head Office within 7 days of occurrence.

Time and date of fault..... Classification of fault.....
Time first report received..... From .....
Place of occurrence.....
Cause of interruption.....
Material damage caused.....
Type of equipment ..... Date erected or jointed.....
Phase or phases involved.....
Switches which cleared fault:

	Substation.	Switch.	Type of relay or trip fuse.	Flag indication.
1.				
2.				
3.				
4.				

		No.	Duration	Substation-hours.
Substations interrupted by automatic tripping of switches ..	1.			
	2.			
	3.			
Substations interrupted by switching operations necessitated for localization or repair ..	1.			
	2.			
	3.			
Total ..			Total ..	

Weather conditions at time of fault.....
Steps already taken to repair fault.....
.....
Remarks and suggestions for prevention of similar occurrences in future.....
.....
.....
Signed.....
District Engineer.

Observations on above.....
.....
Signed.....

Action to be taken.....
.....
Signed.....

FIG. 6

Table 7

Year	Number of lightning faults	Substation-hour interruptions
1935	77	1808
1936	58	892·3
1937	60	1328·96
1938	61	359·80
1939	122	1975·08
1940	36	844·8
1941	19	215·7

individual report indicates that the main trouble now experienced is due to blown fuses, and it is possible that the large residual current in a fault which results from the use of a single coil only on so extensive a system may be a contributory factor in producing this effect. Further improvement might be obtained by splitting up the network into sections, each protected by a separate coil.

It should be mentioned that the characteristics of the network have been changed very appreciably since the installation of the coil, owing to a considerable increase in the mileage of underground cable, and that the range of tappings on the coil is no longer sufficient for tuning purposes. The installation of further coils to remedy this condition is now being considered.

(3.6.2) **Earth Wires.**

Experience has proved the value of the screening effect of overhead earth wires placed above the conductors as protection against lightning. They are installed on all new main lines on the system, but are omitted on spur lines on the ground of economy.

(3.6.3) **Lightning Arresters.**

It is very difficult to assess the usefulness of lightning arresters, as observed results give only negative evidence. Horn gaps are no longer used owing to their doubtful value and the possibility of the steep-tailed wave which their operation leaves on the line causing trouble on transformer windings and terminal apparatus. It is, however, proposed to install at the earliest possible opportunity Thyrite-type arresters at positions where main lines are connected to underground cable sections, in order to protect the pole boxes, cables and terminal apparatus connected to the other end of the cables.

(3.6.4) **Insulation of System.**

Insulation failures have been chiefly due to damage by stone-throwing or gun-shot, brine deposit and ageing of strain insulators and 2-piece pin insulators. No ageing has been noticed in pin insulators made in a single piece.

Sections on which frequent insulation failures have been noted are being dealt with by replacing those types of insulators subject to ageing, and by removing the earth connections from the steel cross-arms on wood-pole lines in cases where a higher insulation value of the system is considered desirable.

(3.6.5) **Pole Boxes.**

The increase in the number of pole-box failures on the system has become alarming, and an analysis of this item shows that the great majority are due to two types of boxes erected in the early days of rural supply. This was due partly to the design of the boxes and partly to the method of installation adopted at that time, jointing having been carried out at ground level and the box lifted into position afterwards. The resulting movement of the cable cores placed the solid compound under severe stress, causing cracking and eventually leading to failure.

It has therefore been considered expedient to embark on a programme of replacement of these boxes before further failures occur.

(3.6.6) **Switchgear Failures.**

The majority of switchgear failures have been due either to open-type current transformers installed in kiosks or to the deterioration of air-break switchgear. The former have been replaced by compound-filled types, and a survey of the existing overhead-line switchgear has been prepared so that replacement of equipment in bad condition can be made as opportunity occurs.

(3.6.7) **Transformer Bushings.**

At one time the bushing insulators fitted to pole-mounting transformers were a frequent cause of trouble. This matter was investigated in conjunction with the manufacturers, the design modified, and the insulator so arranged that any flashover would take place from the stem to the tank. Insulators on all existing transformers were changed, and since this has been done there have been very few further failures.

(3.6.8) **Mechanical Failures.**

Mechanical failures have been chiefly conductor failures due to electro-chemical corrosion in composite conductors, particularly steel-cored copper. Cadmium-copper or plain hard-drawn copper is being used for all new lines.

(4) A STANDARD FORM FOR RECORDING FAULTS

In order that useful analyses may be prepared it is essential that very full reports be made relating to every fault. To prevent the omission of necessary information, a standard form is used. This consists of two parts, one giving preliminary details to be sent in within 24 hours of the occurrence, and the other to be returned within 7 days, giving final details. The latter period is allowed to permit of line patrols and full investigation of the occurrence.

The type of fault report is indicated in Fig. 6, and it is suggested that this form, modified if necessary to make it universally applicable, together with the method of classification detailed in Section 3.5, might be adopted as standard by supply undertakings. The preparation of fault statistics would then be simplified and different undertakings would be able to compare the incidence of faults on their networks.

At the present time, undertakings can only compare one year's operation with another and have no means of telling whether their standard is good or otherwise.

The authors would even go so far as to suggest that the provision of returns relating to e.h.v. faults should become obligatory in the same way that returns are required for specified occurrences under the Factory Acts and the Commissioners' Regulations. These returns should be sent to some technical body who would carry out the work of correlation and make the information available to the supply industry in general.

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